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A STUDY OF THE IMPULSE VALVE FOR UGANDA HYDRAULIC RAM PUMP

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Background

E. Schiller and P. Kahangire carried out an experimental (1) and an analytical study (2) of the automatic hydraulic ram pump. In the analytical study, the impulse valve was assumed to close instantaneously. This restrictive assumption was neccessitated by the lack of knowledge of the dynamic behaviour of the impulse valve at the time. The present study seeks to develop a mathematical model for predicting the dynamic behaviour of the impulse valve as it closes. Such a model will lead us to a better understanding of how the shape of the impulse valve affect the performance of the hydraulic ram. This will enable us to improve the design of the impulse valve for optimum performance of the hydraulic ram.

The Mathematical Model

The accompanying paper (3) describes a mathematical model for an impulse valve with a weighted valve flap. In the mathematical model, the one-dimensional fluid flow equations of the hydram cycle are solved by a numerical finite difference method. The finite difference method is chosen because quite complex physical models can be incorporated into the solution procedure via the finite difference formulation. The computer program contains about 550 lines of FORTRAN statements and it takes about 2.5 minutes to compute a complete hydram cycle (2500 iterations)on an IBM-XT compatible.

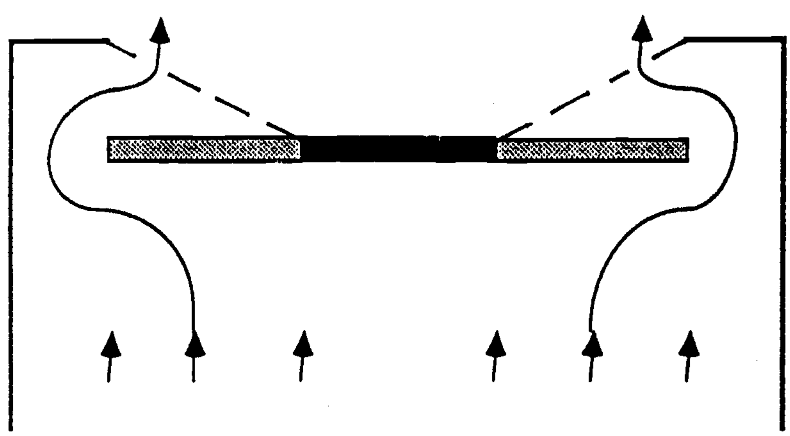


Fig. 1: Schematic diagram of the impulse valve

In the present study, the valve arrangement is different. The valve flap is a rubber disc with a central location hole. The central hole fits into a vertical sleeve which positions it to close upwards onto a perforated (the orifice) conical valve seat (see Fig. 1). As the water flows upwards past the outer edges of the valve flap and into the orifice, a pressure difference is generated between the bottom and top surfaces of the valve flap. As the pressure on the bottom surface is higher, the outer edge of the valve flap is push upwards. If the flow is fast enough, the valve flap closes itself on to the conical valve seat and stops the flow. The mathematical model as described in reference 3 still applies except that there is no period 2. In period 3, the movement of the outer edge of the valve flap is computed from an algebraic expression which gives the relationship between the deflection of the outer edge and the pressure difference between the top and bottom surfaces of the valve flap.

Experimental Investigation

A parallel experimental investigation was carried out to obtain data to test the numerical computational prediction procedure. Experiments were run for different rubber hardness as well as different thickness.

Physical Models

Deflection of Rubber Flap

The rubber valve flap is assumed to deflect under a uniform pressure loading p. The deflection of the outer edge of the rubber flap is given by:

$$y_{max} = \frac{3pa^4(1-\nu^2)}{16Eh^3}\left[\frac{4(1-s^2)(3+\nu)}{(1+\nu)} + \frac{16s^2(1+\nu)(\ln(1/s))^2}{(1-\nu)(1-s^2)} - \frac{4s^2(3+\nu)\ln(1/s)}{(1-\nu)} - \frac{(1-s^4)(5+\nu)}{(1+\nu)}\right]$$

where

- y_{max} is the deflection at the outer edge
- a is the outer radius of rubber disc
- b is the inner radius of rubber disc
- s is the ratio (b/a)
- ν is the Poisson's ratio of rubber

The effective pressure exerting on the rubber disc is computed from the expression

$$p = 0.5\,\rho\,V_a^2\,(C_d + C_a) + 0.5\,V_r^2\,C_r$$

where

- V_a is the velocity at the tip of the valve flap
- V_r is the radial velocity between the valve flap and valve seat
- C_d, C_a, C_r are pressure loss coefficients

The Computer Program

A listing of the computer program is attached. An explanation of the meaning of the variables are given at the beginning of the program.

Results and Discussion

Although the present prediction procedure employs a simple quasi-steady model for the closure of the impulse valve flap, it is possible to procure agreement with the experimental results of the rate of closure of the valve flap (see Fig. 2 to 7) by suitable adjustment of the pressure coefficient C .

The theoretical predictions of global performance data (such as volumetric flow rates through the impulse and the delivery valves, and the number of beats per minute) are compared with the experimental results in Tables 1 and 2. The trend shown by the experimental results are well predicted by the present model. However, the predicted water flowrates through both the impulse and delivery valves fall at a slower rate than the experimental values.

References

1. Schiller, E.J., Kahangire, P. (1984) "An experimental investigation and design of hydraulic ram pumps". International Journal for Development Technology, Vol. 2, 173 - 183.

2. Schiller, E.J., Kahangire, P. (1984) "Analysis and computerised model of the automatic hydraulic ram pump". CAN. J. CIV. ENG. Vol. 11.

3. Goh, S.Y. (1988) "A study of the dynamic characteristics of the impulse valve of the hydraulic ram". Paper presented at the 6th IWRA World Congress on Water Resources, May 29 - June 3, 1988, Ottawa, Canada.

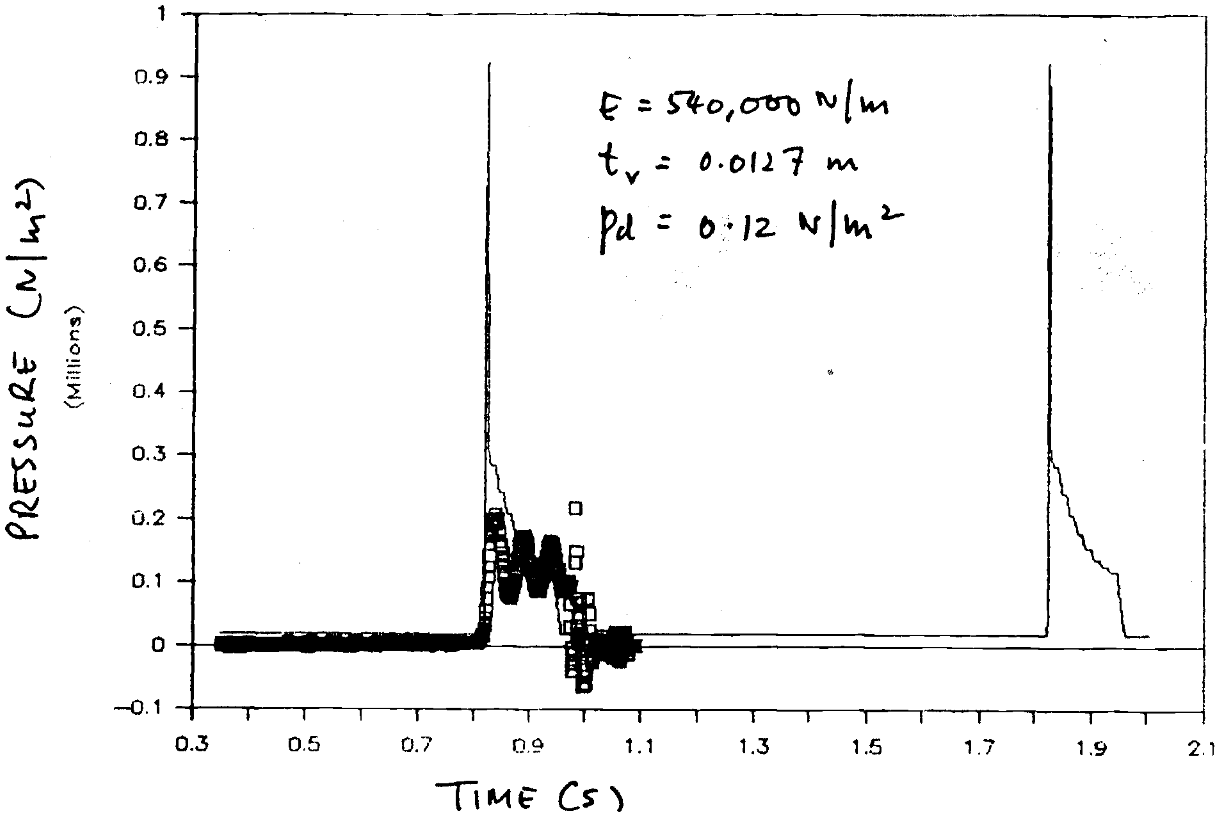
TABLE 1

	Expt.	Theory	Expt.	Theory	Expt.	Theory
Elasticity	540000	540000	540000	540000	540000	540000
Thickness	.00635	.00635	.00953	.00953	0.0127	0.0127
Delivery Pressure (psig)		60	54	60		60
Q (litres/min)		19.3	21.2	40.6		72
q (litres/min)		0.548	0	1.45		2.33
Beats (per min)		138.5	51	85.5		57
Delivery Pressure		50	50	50	52	50
Q (litres/min)		19.9	23.7	41.1	34.5	72.8
q (litres/min)		0.79	0.16	1.83	0.28	2.87
Beats (per min)		142.3	52	86.6	49	57.6
Delivery Pressure		40	37	40	37	40
Q (litres/min)		20.1	31.6	41.6	43	73.6
q (litres/min)		1.11	0.98	2.38	1.46	3.68
Beats (per min)		144.4	58	87.7	51	58.2
Delivery Pressure	28	30	30	30	30	30
Q (litres/min)	8.4	19.3	33.7	41.5	48.1	74.5
q (litres/min)	0	1.53	1.58	3.24	2.52	5.01
Beats (per min)	89	138.4	58	87.5	51	58.9
Delivery Pressure	21	20	17	20	17	20
Q (litres/min)	14.5	17.9	43.3	42.8	59.1	75.4
q (litres/min)	1.08	2.25	4.8	5.09	6.36	7.66
Beats (per min)	102	128.6	62	90.3	57	59.6
Delivery Pressure	10	10	12	10		10
Q (litres/min)	18.4	19	44.2	43.6		74.9
q (litres/min)	4.32	4.91	8.61	10.5		15.3
Beats (per min)	100	136.4	63	92.1		59.2

TABLE 2

	Expt.	Theory	Expt.	Theory
Elasticity	1510000	1510000	1510000	1510000
Thickness	0.00635	0.00635	0.00953	0.00953
Delivery Pressure (psig)		60	58	60
Q (litres/min)		36.3	40.9	80.8
q (litres/min)		1.29	0.16	2.48
Beats (per min)		93.7	42	51.3
Delivery Pressure		50	50	50
Q (litres/min)		36.7	45.2	82.3
q (litres/min)		1.64	0.54	3.07
Beats (per min)		94.7	43	52.3
Delivery Pressure	41	40	41	40
Q (litres/min)	16	36.5	49.1	83.1
q (litres/min)	0.245	2.11	0.78	3.92
Beats (per min)	68	94.4	44	52.8
Delivery Pressure	30	30	29	30
Q (litres/min)	24	37.1	55.5	84
q (litres/min)	1.25	2.93	1.88	5.33
Beats (per min)	74	95.7	45	53.3
Delivery Pressure	20	20	23	20
Q (litres/min)	23.2	37.7	62.1	84.9
q (litres/min)	1.98	4.56	2.94	8.13
Beats (per min)	73	97.3	46	53.9
Delivery Pressure	11	10	10	10
Q (litres/min)	25.9	38.5	81.3	83.6
q (litres/min)	5.64	9.42	10.9	16.1
Beats (per min)	71	99.5	52	53.1

FIG. 2a & 2b : VARIATION OF PRESSURE & IMPULSE VALVE DISPLACEMENT DURING CLOSURE.



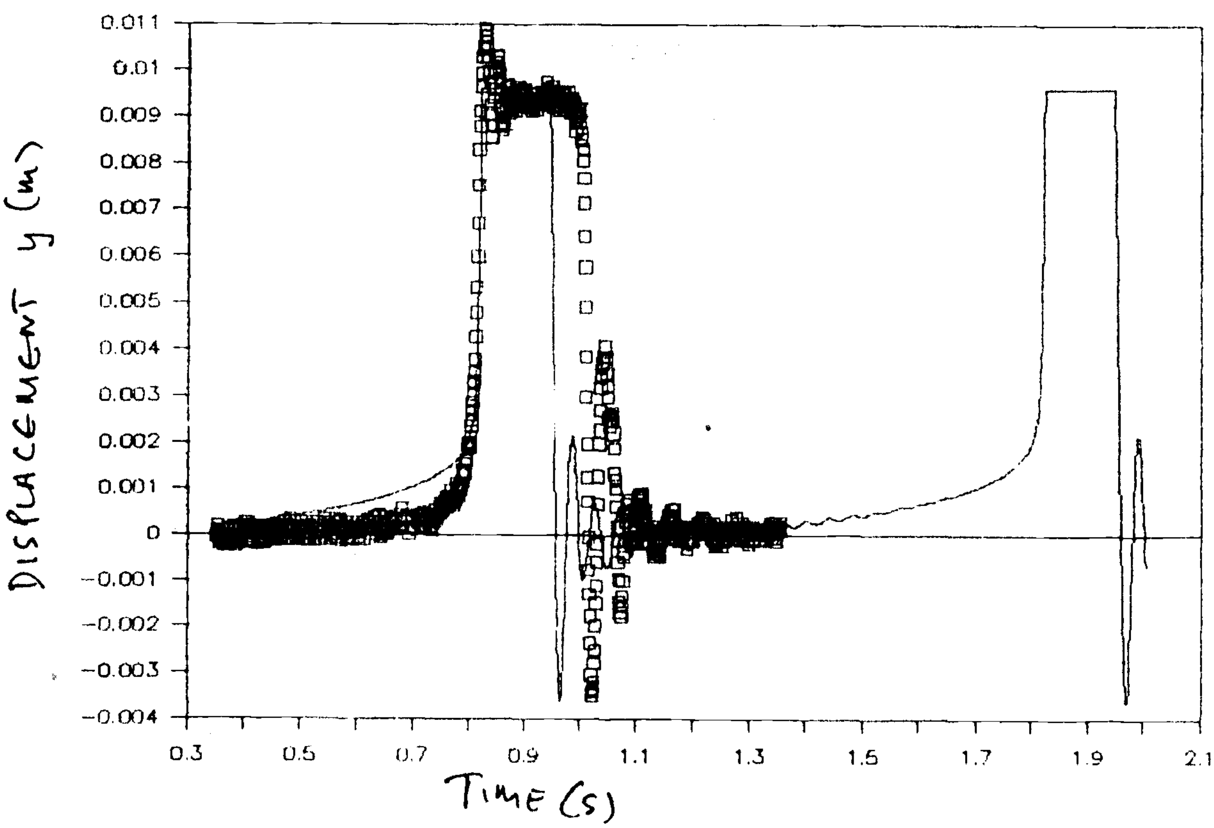
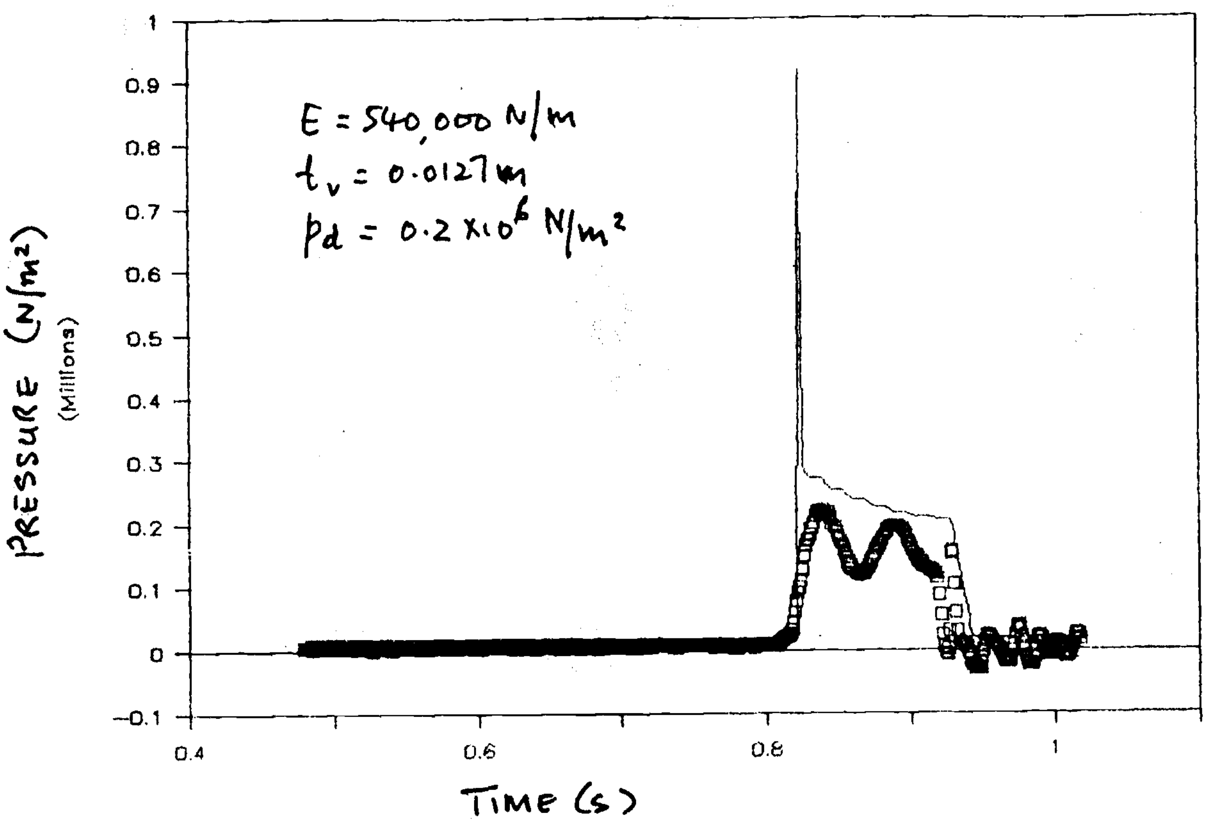


FIG. 3a & 3b : VARIATION OF PRESSURE & IMPULSE VALVE DISPLACEMENT DURING CLOSURE



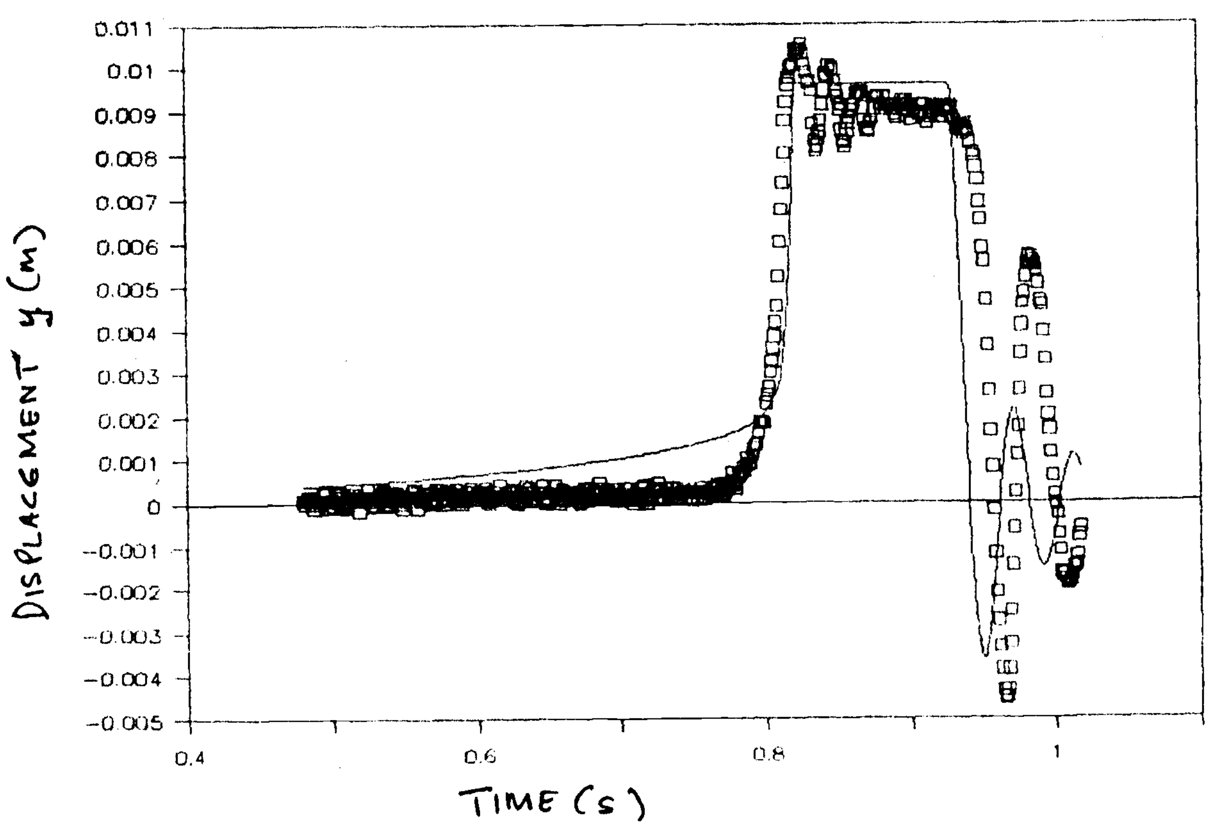
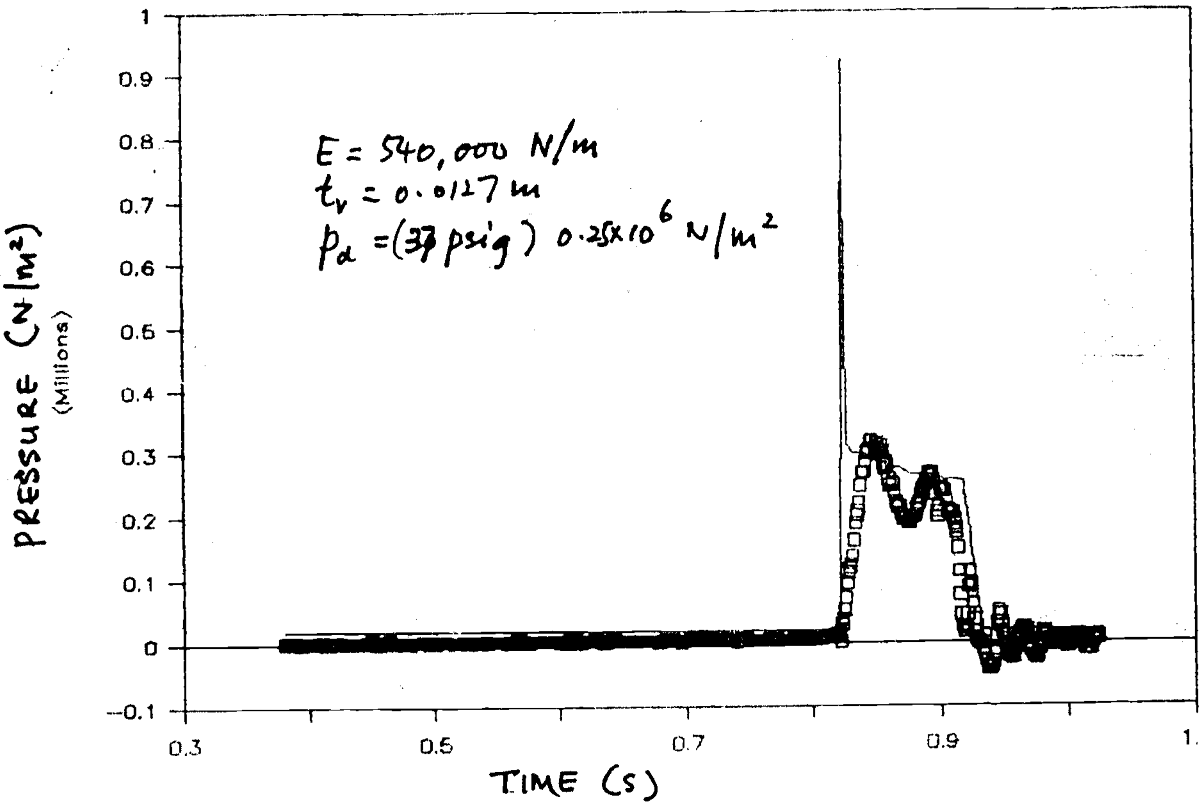


FIG. 4a & 4b ~~FIG 3a & 3b~~ : VARIATION OF VALVE DISPLACEMENT & PRESSURE DURING VALVE CLOSURE



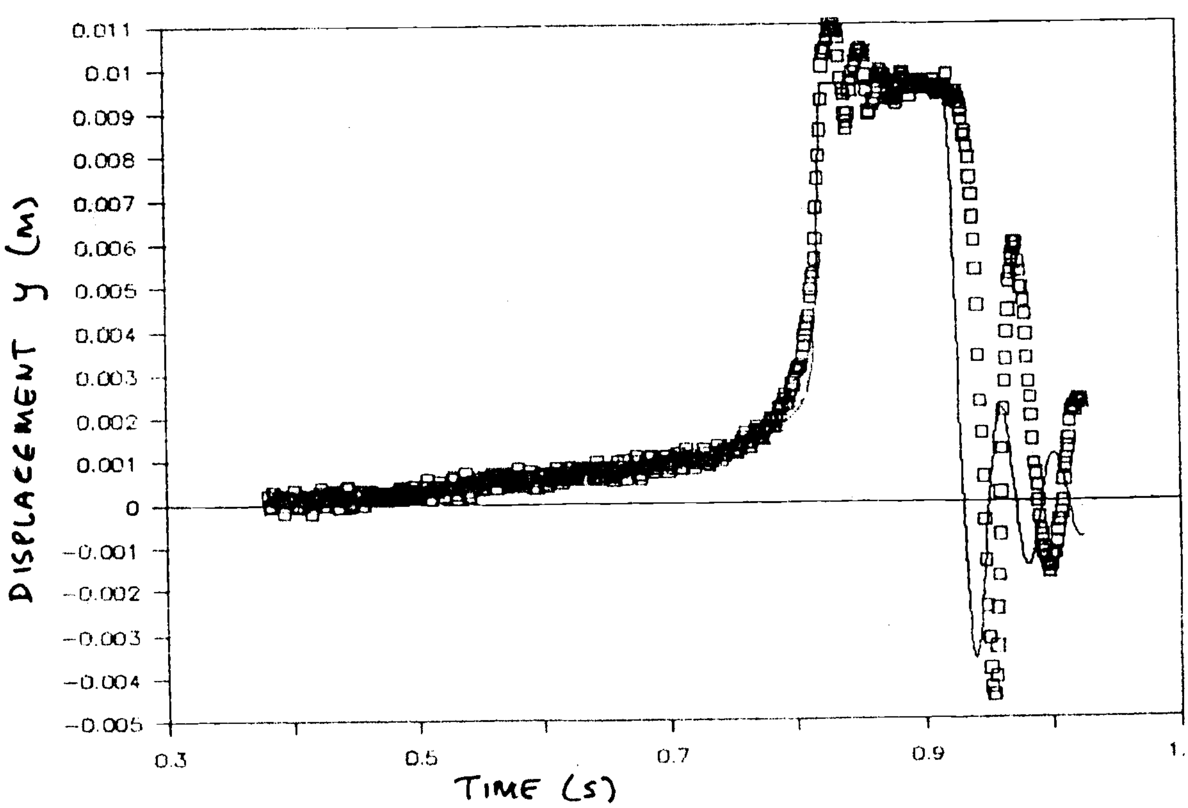
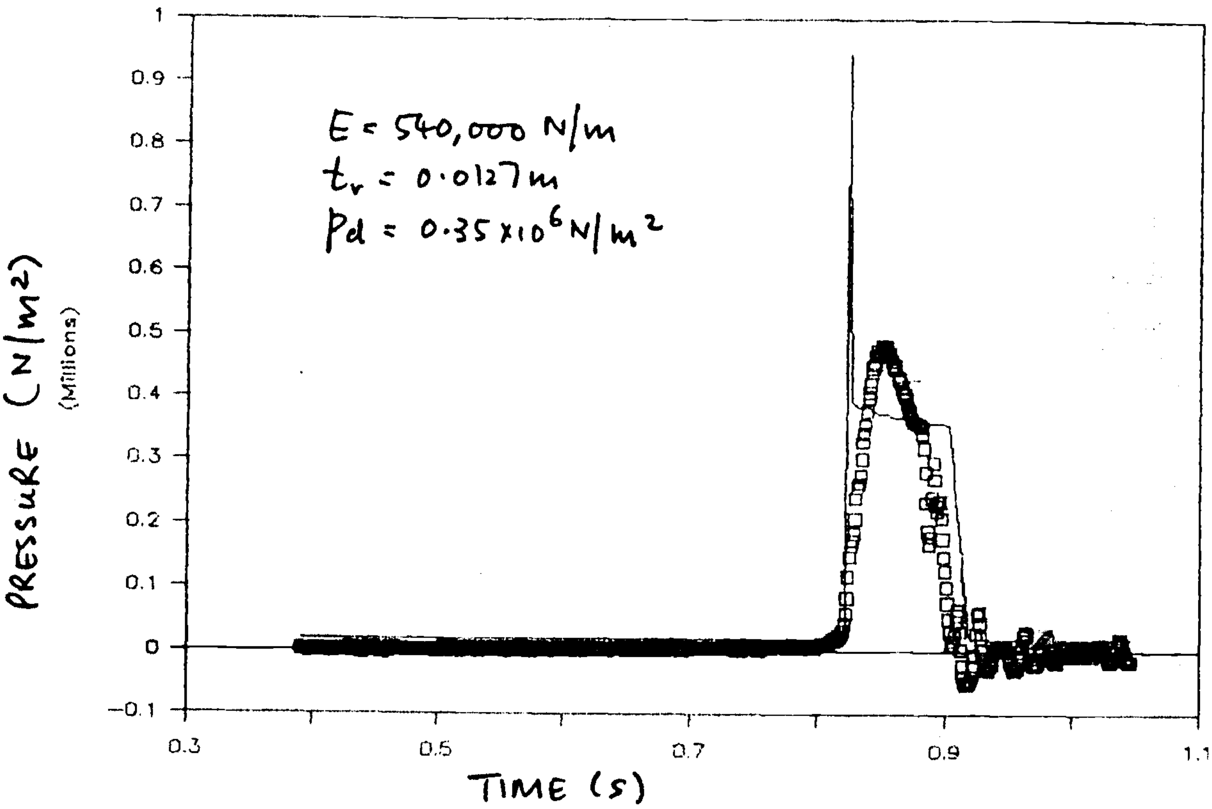


FIG. 5a & 5b : VARIATION OF PRESSURE & IMPULSE VALVE DISPLACEMENT DURING CLOSURE



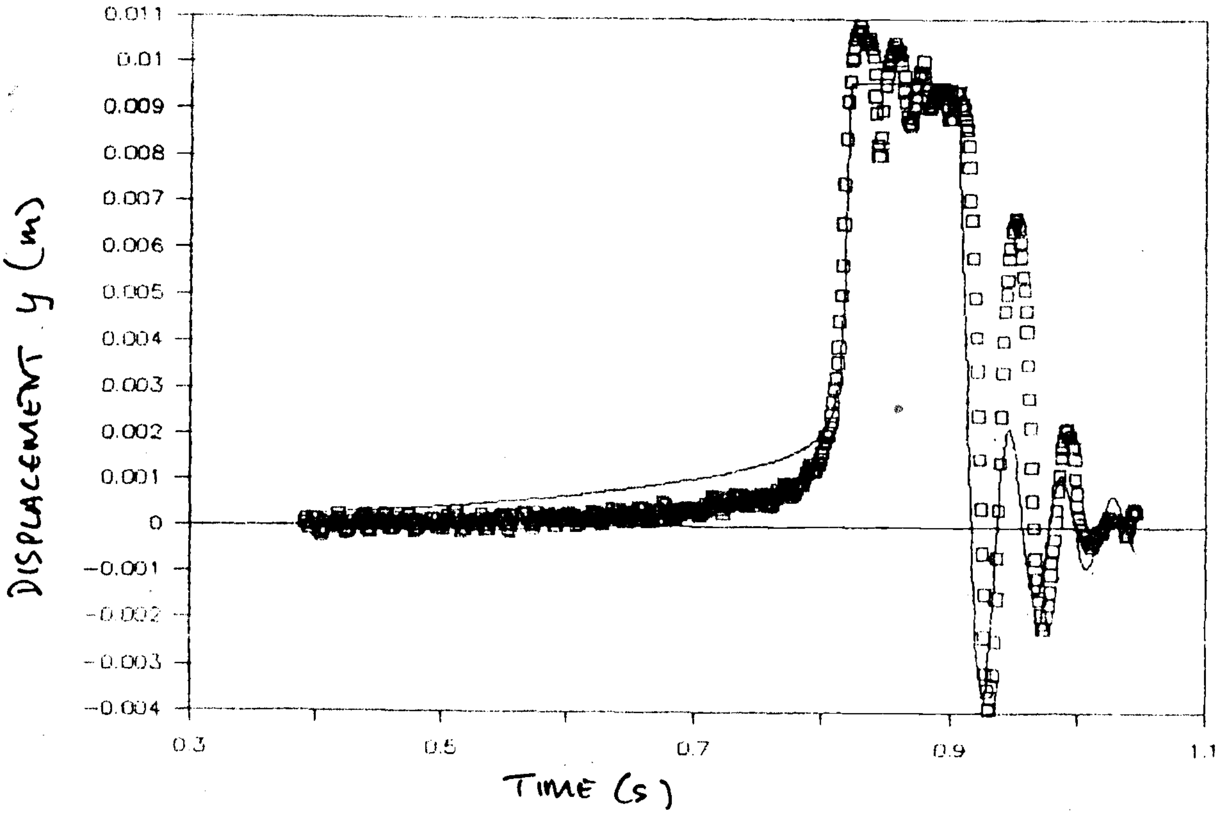
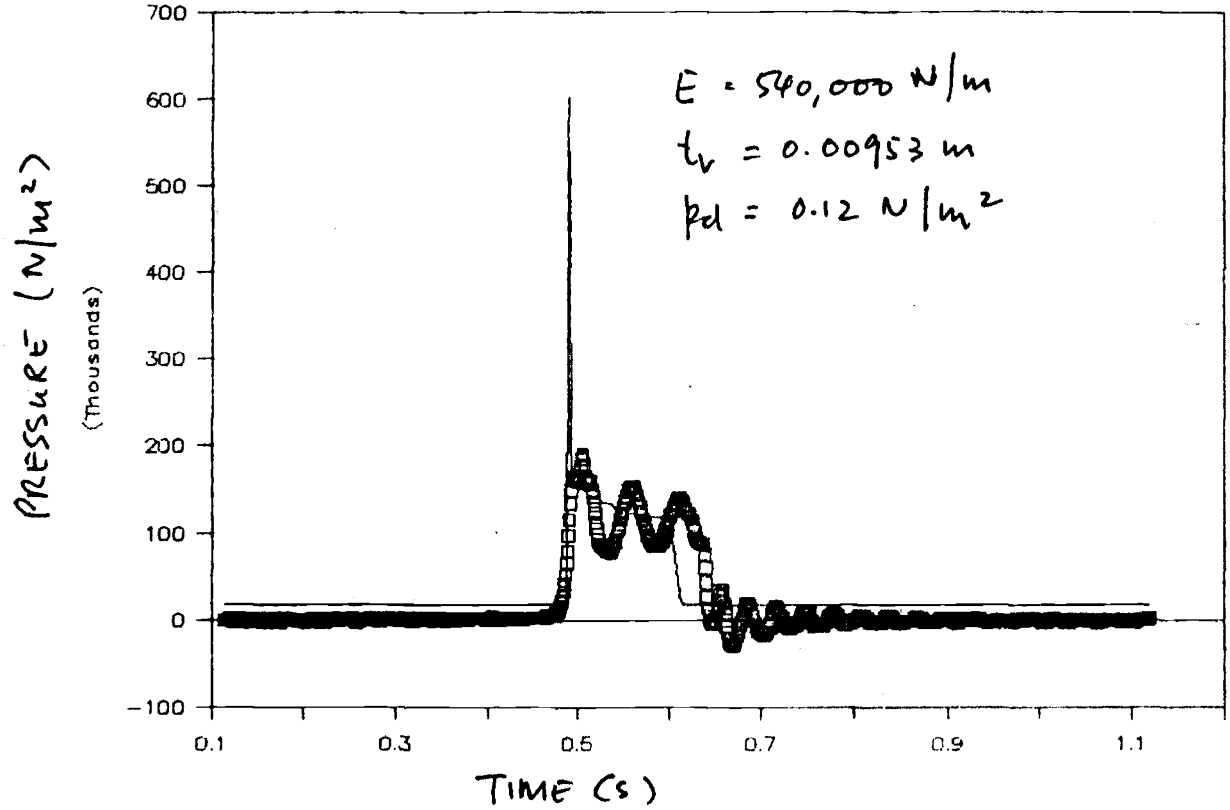


FIG. 6a & 6b: VARIATION OF PRESSURE & IMPULSE VALVE DISPLACEMENT DURING CLOSURE



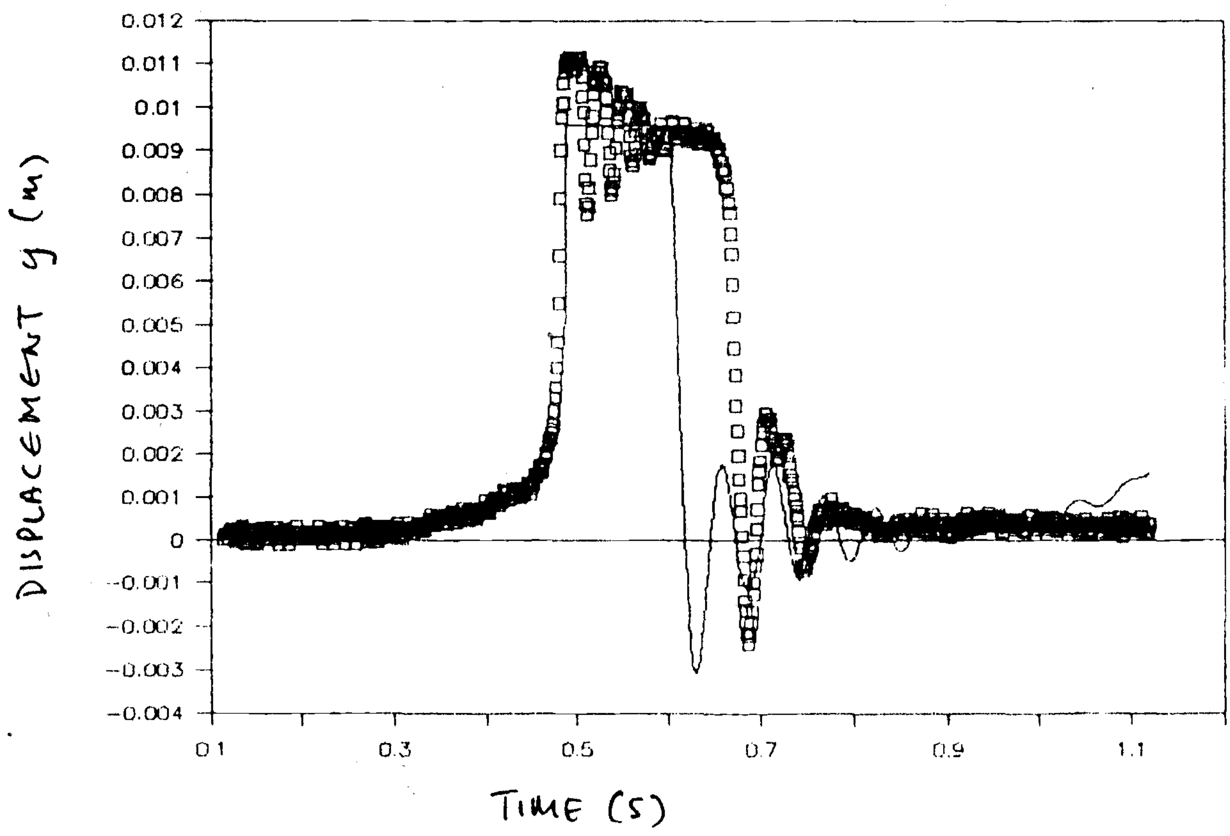
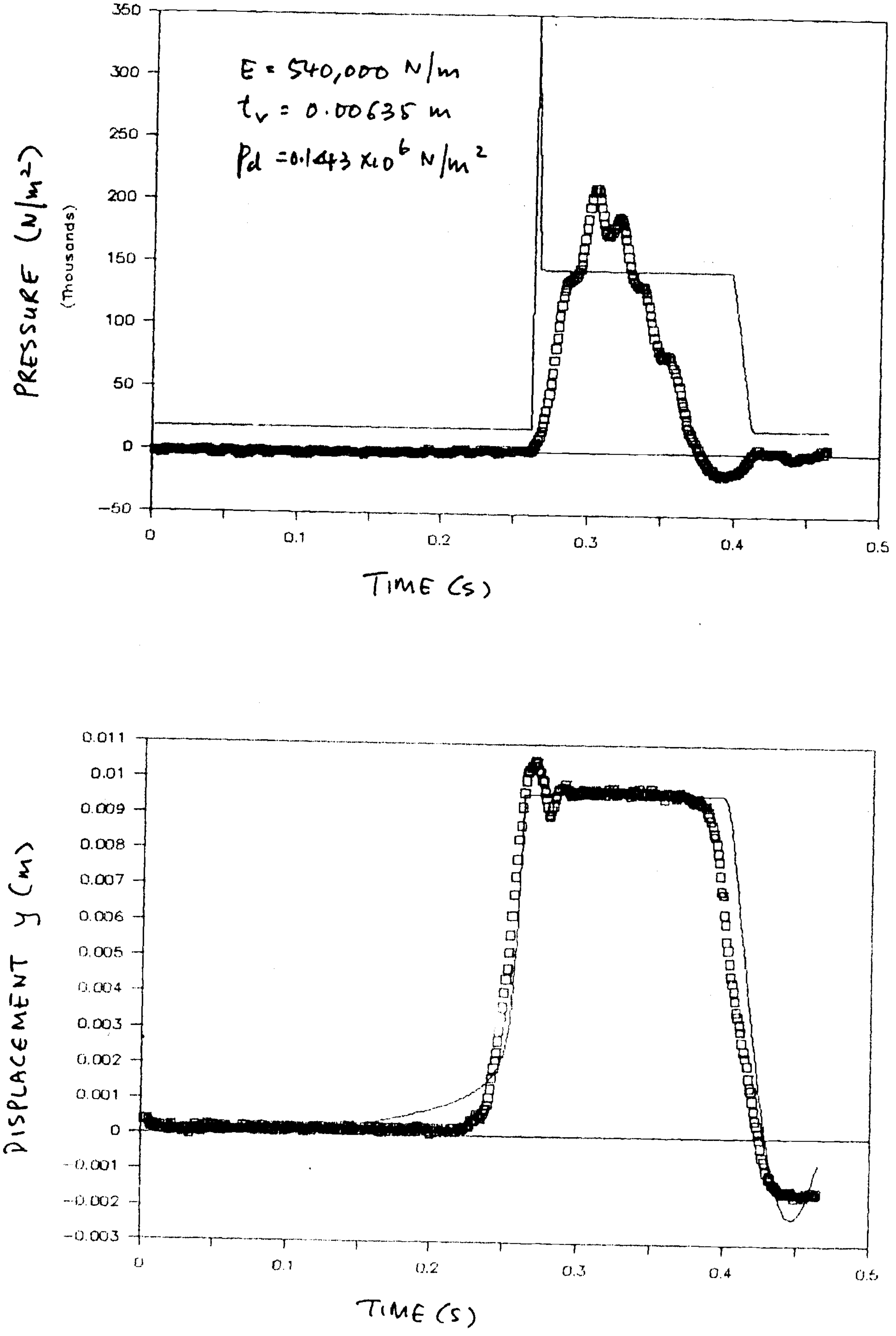


FIG. 7a & 7b : VARIATION OF PRESSURE & IMPULSE VALVE DISPLACEMENT DURING CLOSURE



```
c ------------------------------------------------------------------------
c     PROGRAM FOR PREDICTING THE PERFORMANCE OF A HYDRAULIC RAM PUMP
c
c               VERSION 2.0 (26TH MAY 1988) (FORTRAN-77)
c
c     WASTE VALVE TYPE: RUBBER DISC FLAP CLOSING UPWARDS ONTO
c                       CONICAL MULTI-HOLE VALVE SEAT
c
c ------------------------------------------------------------------------
c     For theoretical background, please refer to:-
c     ' A study of the dynamic characteristics of the
c       impulse valve of the hydram ' by S.Y. Goh
c     Paper presented at the 6th IWRA World Conference on Water
c     Resources, Ottawa, Canada, May 29 - June 3, 1988.
c
c*************************************************************************
c
c     Put ncycle=2 to compute over 2 cycles
c         nwrite=0 if you do not want a printout of ti,yi,vi etc.
c         -------- drive pipe ----------
c          h  is the water drive head
c         dp  is the internal diameter of drive pipe
c         al  is the length of drive pipe
c         tp  is the wall thickness of drive pipe
c        ------- impulse valve ---------
c         a   is the external radius of rubber valve flap
c         b   is the internal radius of rubber valve flap
c         tv  is the thickness of the rubber valve flap
c         er  is the Modulus of Elasticity of the rubber
c       poisr is the Poisson's ratio of the rubber
c       cdamp is the damping coefficient of valve flap vibration
c         wn  is the frequency of valve flap vibration
c       freq  is factor in frequency formula for valve flap vibration
c        dor  is the effective (single hole) orifice diameter
c         do  is the actual hole diameter of each single hole
c        alo  is the length of the orifice holes
c         de  is the impulse valve chamber diameter
c      gapmax is the maximum reference gap at outer edge
c        ymax is the gap when flap is undistorted (flat)
c        ------- delivery valve --------
c        ddv  is the effective (single hole) delivery valve diameter
c        ------- properties ------------
c        den  is the density of water
c        vis  is the viscosity of water
c         ew  is the Bulk Modulus of water
c         es  is the Modulus of Elasticity of steel
c       pois  is the Poisson's ratio for steel
c        ----------- output -------------
c      qwlpm  is the flowrate through the impulse valve (litres per min)
c      qtlpm  is the flowrate through the delivery valve(litres per min)
c       beat  is the number of beats (cycles) per minute
c
c     The results will be stored in a file 'RESULT'.
c     This file can be printed out or examined through an editing
c     program.
c ------------------------------------------------------------------------
      common/gen/ctp,cte,ctda,ctr,ap,arpo,arop,vpi,vpim1
     1      ,voi,vpmax,qwaste,pr,dt,pstat
      common/dimen/h,dp,tp,al,alo,do,dor,de,ddv
      common/prop/den,vis,ew,es,pois
      common/press/pa,papsi,pdgpsi
      common/coeff/cp,cdv,cd,ca,cr1,cr2,co
      common/flap/a,b,tv,er,poisr,cdamp,freq
```

```
      common/osc/vmass,wn,cdampt
c ---------------------------------------------------------------------
      open(3,file='result')
c ....  iteration control parameters ........
      data ncycle,nmax,nitn,nwrite/2,10000,10,1/
c
c ....  specify time step for each period
      data dt1,dt2,dt3,dt44,dt4,dt5,dt6/
     1    .001,.0005,.0005,.00005,.0005,.0005,.0005/
c
c ....  specify timestep for printout
      data dtpr0,dtpr1,dtpr2,dtpr3,dtpr4,dtpr5,dtpr6/
     1     .001,.001,.001,.001,.001,.001,.001/
c
c ...rubber flap dimensions and constants
      a=.054
      b=.0151
      tv=.00635
      er=540000.
      cdamp=2.6
      freq=4.35
      ro=a-b
      dv=2.*a
      dvi=2.*b
c ...dimensions of hydram
      h=1.89
      dp=0.053
      tp=.0032
      al=9.85
      alram=.40
      alo=.0125
      do=.0045
      dor=.0517
      de=8.*.0254
      ddv=.0311
      ymax=.0096
      gapmax=.012
c... property constants and pressure
      den=1000.
      vis=.00116
      pi=3.1416
      ew=2.17e9
      es=1.90e11
      pois=.3
      poisr=.4
      ef=1./ew+(5.-4.*pois)*.25*dp/(tp*es)
      ef=1./ef
      papsi=14.7
      pa=101325.
c .... pdgpsi is the delivery pressure (psig)
      pdgpsi=21.
      pd=pa*(pdgpsi+papsi)/papsi
      pdg=pd-pa
      pstat=den*9.81*h
c
c  cccccccccccccc   pressure loss coefficients  cccccccccccccccc
c
      cp=3.5
      ce=0.
      cd=1.3
      ca=1.3
      cr1=1.
      cr2=-1.
      co=1.
      cdv=.3
c ... other weighting constants
```

```
      fadv=.2
      eff=1.
      fydot=.75
      fdt=1.
      pcr=1.
      cr=cr1
      cop=co
c  aaaaaaaaaaaaaaaaaaa compute areas and area ratios  aaaaaaaaaaaaaaaa
      pid4=.25*pi
      ao=pid4*dor*dor
      aa=pid4*(de*de-dv*dv)
      av=pid4*(dv*dv-dvi*dvi)
      ap=pid4*dp*dp
      ae=pid4*de*de
      arm=ymax*pi*dv
      adv=pid4*ddv*ddv
      aroa=ao/aa
      arorm=ao/arm
      arop=ao/ap
      arpo=ap/ao
      arva=av/aa
      aroe=ao/ae
      ardvp=adv/ap
c ******* calculate area-corrected pressure coefficients ***********
      cte=aroe*aroe*ce
      ctp=arop*arop*cp
      ctd=aroa*aroa*cd
      cta=aroa*aroa*ca
      ctda=ctd+cta
      ctr=arorm*arorm*cr
      ct=ctd+cta+ctr
c  ooooooooooooooooooooo oscillation parameters  oooooooooooooooooooooo
      vmass=av*tv*den
      det=den*9.81*(a**4-b**4)*(1.-poisr*poisr)
      wn=freq*sqrt(er*tv*tv/det)
      cdampt=cdamp*0.5*den*av
c
c  bbbbbbbbbbbbbbbbbbbbb  start of each cycle  bbbbbbbbbbbbbbbbbbbbbb
      nc=0
      cmax=9.81*den*h
      tilim=100.
      tstart=0.
      xi=0.
      xim1=0.
      yc=0.
c
  10  vpi=1.0e-20
      voi=1.0e-20
      vp4=0.
      npe=0
      qiv=0.
      qdv=0.
      qwaste=0.
      vpim1=0.
      vomax=0.
      vpmax=0.
      vpt=0.000001
      yim1=0.
      yi=0.
      t1=tstart
      t2=tstart
      ti=tstart
      dt=dt1
      dtpr=dtpr1
      np=1
      akti=1.
```

```
      vol=0.
      yv=yi+xi
      yvm1=yim1+xim1
c
c  ttttttttttt   start of time step within each cycle  tttttttttttttt
c
      do 730 i=2,nmax
      dt0=dt
      if(dtpr0.ne.100.)dtpr=dtpr0
      ns=dtpr/dt
      go to (100,200,300,400,500,600),np
c  ***************** compute velocity in drive pipe  ******************
c
c  1111111111111111111111111   period one  11111111111111111111111111
c
 100  co=0.
      ctda=0.
      ctd=0.
      ctr=0.
      tim1=ti
      ti=ti+dt
      vol=vol+ap*vpi*dt
      yvol=vol/ae
      if(yvol.ge.yc)go to 110
      vpim1=vpi
      call vpipe
      if(vpi.gt.vpmax)vpmax=vpi
      call oscil(xi,xim1,dt0,dt,xip1)
      yi=xip1
      xim1=xi
      xi=xip1
      if(float(i-2)/float(ns).ne.float((i-2)/ns))go to 105
      if(nwrite.eq.1)write(3,30)i,ti,yi,vpi,pr,qtot,np
 105  continue
      go to 730
 110  write(*,*)'PERIOD ONE PASSED'
      np=3
      dt=dt3
      dtpr=dtpr3
      t1=ti
      go to 730
c
c  222222222222222222222222   period two  2222222222222222222222222222
c
 200  co=cop
      ctd=aroa*aroa*cd
      cta=aroa*aroa*ca
      ctda=ctd+cta
      ctr=arorm*arorm*cr
      tim1=ti
      ti=ti+dt
      if(vpi.ge.vpt)go to 210
      vpim1=vpi
      call vpipe
      if(vpi.gt.vpmax)vpmax=vpi
      qwaste=qwaste+ap*vpi*dt
      go to 700
 210  write(*,*)'PERIOD TWO PASSED'
      np=3
      dt=dt3
      dtpr=dtpr3
      t2=ti-t1
      go to 730
c
c  3333333333333333333333333   period three  3333333333333333333333333
c
```

```
 300  co=cop
      iydot=0
      tim1=ti
      ti=ti+dt
      if(ti.gt.tilim)dt=fdt*dt3
      yip0=1.
      vpim1=vpi
c
 310  gap=ymax-yi
      if(gap.lt.0.)gap=0.00000001
      if(gap.gt.gapmax)gap=gapmax
      cr=cr1+cr2*(gap/gapmax)**pcr
      ctd=aroa*aroa*cd
      cta=aroa*aroa*ca
      ctda=ctd+cta
      ar=pi*dv*gap
c
      arvo=av/ao
      aror=ao/ar
      ctr=aror*aror*cr
      ydot=(yi-yim1)/dt
c
      teta=asin(yi/ro)
      rocos=ro*cos(teta)
      dvol=pi*ro*ro*ydot*(a/rocos+.66667)
c
      var=aroa*voi-ydot-dvol/aa
      rvadvo=var/voi
      ctda=ctda*rvadvo*rvadvo
      if(var.lt.0.)ctda=-ctda
c
      vr=aror*voi-dvol/ar
      rvrdvo=vr/voi
      ctr=cr*rvrdvo*rvrdvo
      if(vr.lt.0.)ctr=-ctr
c
      call vpipe
c
      ct=ctda+ctr
      p35=.5*den*voi*voi*ct
      if(p35.gt.cmax)p35=cmax
c
      call ydist(p35,yip1)
c
      if(yip1.lt.ymax)go to 320
      write(*,*)'PERIOD THREE PASSED'
      yi=ymax
      xi=0.
      xim1=0.
      voi=0.
      vpi=0.
      vomax=0.
c      write(3,30)i,ti,yi,vpi,pr,vomax,np
c      write(3,48)
      np=4
      tilim=.8*ti
      t3=ti-t2-t1
      sq=0.
      ac=sqrt(ef/den)
      pe=2.*al/ac
      hvpi=0.
      t40=ti
      np44=100
      dt=dt4
      dtpr=dtpr4
      dpmaxg=vpmax*sqrt(den*ef)
```

```
      pmaxg=pstat+dpmaxg
      pmax=pmaxg+pa
      akemax=.5*den*ap*al*vpmax*vpmax
      pdgs=pdg-pstat
      werg=  .5*ap*al*(pdg*pdg-pstat*pstat)/ew
      epip=(2.-2.5*pois)*pi*dp*dp*(al-alram)/(8.*es)
      serg= epip*(pdg*pdg-pstat*pstat)
      qtot=(eff*akemax-serg-werg)/pdg
      go to 730
 320  continue
      iydot=iydot+1
      if(yip1.gt.yim1)go to 321
      yip1=yim1+fydot*(yi-yim1)
      yi=yip1
 321  continue
      if(abs(yip1-yip0).lt..0001)go to 330
      yip0=yip1
      if(iydot.gt.nitn)go to 330
      go to 310
c
 330  yim1=yi
      yi=yip1
      if(vpi.gt.vpmax)vpmax=vpi
      qwaste=qwaste+ap*vpi*dt
c
      call oscil(xi,xim1,dt0,dt,xip1)
c
      yvp1=yip1+xip1
      xim1=xi
      xi=xip1
      yvm1=yv
      yv=yvp1
c
      if(float(i-2)/float(ns).ne.float((i-2)/ns))go to 730
      if(nwrite.eq.1)write (3,30)i,ti,yv,vpi,pr,yi,np
      go to 730
c
c  4444444444444444444444  period four  444444444444444444444444444
c
 400  if(np44.ne.100)go to 460
      dt=dt44
      ns=dtpr/dt
      np44=0
      np41=41
      qpe=.25*pe
      tadv=0.
      slope=pmaxg/qpe
      pmt=pmaxg
      pmrt=0.
      prt=0.
      dsq=0.
c   ppppppppppp determine maximum pressure reached pppppppppppppp
c
      do 440 k=1,1000
      itn=1
      dsqt=dsq
      prtm1=prt
      pmtm1=pmt
      tim1=ti
      ti=ti+dt
      t400=ti
      t41=ti-t40
      tqpe=qpe-t41
      if(tqpe.lt.dt)go to 450
 410  prt=prtm1+slope*dt
      if(pmrt.lt.prt)pmrt=prt
```

```
      if(prt.lt.pdg)go to 420
      tadv=tadv+dt
      fradv=tadv/qpe
      pmpd=2.*(prt-pdg)/den
      vp4=fadv*fradv*cdv*adv*sqrt(pmpd)/ap
      dq=ap*vp4*dt
      dsq=dsqt+dq
      sq=dsq
      dqtot=qtot-dsq
      pmt=pmtm1-(pmtm1-pdg)*dsq/qtot
      slope=(pmt-prtm1)/(tqpe+dt)
      itn=itn+1
      if(itn.le.5)go to 410
      go to 430
 420  vp4=0.
 430  continue
      if(float(k-2)/float(ns).ne.float((k-2)/ns))go to 440
      if(nwrite.eq.1)write (3,30)k,ti,yi,vp4,prt,dqtot,np41
 440  continue
 450  dt=dt4
      np41=42
c      write (3,30)k,ti,yi,vp4,pmrt,dqtot,np41
 460  continue
      tim1=ti
      ti=ti+dt
c
      anpe1=t400+float(npe)*pe
      anpe2=anpe1+.5*pe
      if(ti.ge.anpe1.and.ti.lt.anpe2)go to 480
      npe=npe+1
      to=ti
      tm=ti+.5*pe
c
      do 470 in=1,50
      ti=ti+dt
      if(ti.ge.tm)go to 475
      if(float(in-2)/float(ns).ne.float((in-2)/ns))go to 470
      if(nwrite.eq.1)write (3,30)in,ti,yi,hvpi,pr,qtot,np
 470  continue
 475  ti=tm
      go to 485
 480  continue
c
      pr=pmt-(pmt-pdg)*sq/qtot+1.e-20
      if(pr.le.pdg)go to 485
      pmpd=2.*(pr-pdg)/den
      vp4=cdv*adv*sqrt(pmpd)/ap
      dq=ap*vp4*dt
      sq=sq+dq
      vpi=vp4
      hvpi=.5*vpi
      qdv=qdv+ap*vpi*dt
 485  continue
      if(float(i-2)/float(ns).ne.float((i-2)/ns))go to 490
      if(nwrite.eq.1)write(3,30)i,ti,yi,hvpi,pr,qtot,np
 490  continue
      qstop=qtot-1.e-10
      if(sq.lt.qstop)go to 730
      write(*,*)'PERIOD FOUR PASSED'
      np=5
      dt=dt5
      dtpr=dtpr5
      dt50=2.*al/ac
      t50=ti
      t60=ti+dt50
      t4=ti-t3-t2-t1
```

```
      go to 730
c
c  5555555555555555555555555  period five  55555555555555555555555555555
c
 500  tral=2./(den*ap*al)
      rerg=serg+werg
      vp5=-sqrt(rerg*tral)
      p50=pdg
      p60=pstat-.5*den*vp5*vp5
c
      xi=ymax
      xim1=ymax
c
      do 510 it=1,2000
      tim1=ti
      ti=ti+dt
      vpi=(ti-t50)*vp5/dt50
      voi=vpi*arpo
c
      pr=p50-(ti-t50)*(p50-p60)/dt50
c
      call oscil(xi,xim1,dt0,dt,xip1)
      yi=xip1
      xim1=xi
      xi=xip1
c
      if(ti.ge.t60)go to 520
      if(float(it-2)/float(ns).ne.float((it-2)/ns))go to 510
      if(nwrite.eq.1)write(3,30)it,ti,yi,vpi,pr,qtot,np
 510  continue
c
 520  vpi=vp5
      vp6=vp5
      kt5=1.+cp+ce
      pr=pstat-.5*den*vpi*vpi
      pr6=pr
c      write(3,30)i,ti,dt,vpi,pr,vomax,np
c      write(3,50)
      write(*,*)'PERIOD FIVE PASSED'
      np=6
      dt=dt6
      dtpr=dtpr6
      t5=ti-t4-t3-t2-t1
      t60=ti
      yc=0.
      go to 730
c
c  6666666666666666666666666  period six  66666666666666666666666666666
c
 600  tim1=ti
      ti=ti+dt
      tg=ti-t50
      vpin=-vpi
      re=den*vpin*dp/vis
      if(re.gt.2100)go to 610
      f=64./re
      go to 620
 610  f=.316/(re**.25)
 620  continue
      akt=1.+ctp+cte+f*al/dp
      bb=-9.81*h/al-.5*vpin*vpin*akt/al
      vpipn=bb*dt+vpin
      vpin=vpipn
      vpi=-vpin
      voi=vpi*arpo
      pr=pstat-.5*den*vpi*vpi
```

```
      yc=yc+vpin*dt*ap/ae
      call oscil(xi,xim1,dt0,dt,xip1)
      yi=xip1
      xim1=xi
      xi=xip1
c
      if(vpi.ge.0.)go to 640
      if(float(i-2)/float(ns).ne.float((i-2)/ns))go to 630
      if(nwrite.eq.1)write(3,30)i,ti,yi,vpi,pr,yc,np
 630  continue
      go to 730
 640  nc=nc+1
      write(*,*)'PERIOD SIX PASSED'
      t6=ti-t5-t4-t3-t2-t1
      beat=60./(ti-tstart)
      if(nc.ge.ncycle)go to 740
      tstart=ti
      go to 10
c
c oooooooooooooooooooooo  output control  oooooooooooooooooooooooooooooo
c
 700  if(i.ne.2)go to 710
c      write (3,47)
c      write (3,40)cp,cdv,cd,ca,cr,cop,pdgpsi
c      write (3,46)
 710  if(float(i-2)/float(ns).ne.float((i-2)/ns))go to 730
      if(nwrite.eq.1)write (3,30)i,ti,yi,vpi,pr,var,np
 730  continue
 740  continue
      write(3,54)
      write(3,52)t1,t2,t3,t4,t5,t6,beat
      write(3,51)
      qwcycle=qwaste*1000.
      qtcycle=qtot*1000.
      write (3,30)i,ti,yc,vpmax,pr,pmaxg,np
      qwlpm=qwaste*beat*1000.
      qtlpm=qtot*beat*1000.
      write (3,53)
      write (3,52)akemax,werg,serg,qwcycle,qtcycle,qwlpm,qtlpm
      write (3,43)qwlpm
      write (3,44)qtlpm
      write (3,45)beat
      close(3)
  30  format(i5,5x,5(1pe10.3),i5)
  40  format(6f10.3,1pe10.3)
  52  format(7(1pe10.3))
  43  format(//34h  THE WASTE WATER FLOWRATE IS     ,f10.3,27h
     1LITRES PER MINUTE)
  44  format( /34h  THE DELIVERY WATER FLOWRATE IS  ,f10.3,27h
     1LITRES PER MINUTE)
  45  format( /34h  THE NUMBER OF BEATS IS          ,f10.3,27h
     1 BEATS PER MINUTE)
  46  format(//64h   i          t(i)      y(i)      vp(i)       pr       v
     1omax    np)
  48  format(//65h   i          t(i)       sq       vp(i)       pr
     1qtot      np)
  49  format(//65h   i          t(i)     period     vp(i)       pr       v
     1omax      np)
  50  format(//65h   i          t(i)       yc       vp(i)       pr       v
     1omax      np)
  51  format(//65h   i          t(i)       yc       vpmax       pr      pm
     1axg       np)
  47  format(//67h        cp         cdv       cd        ca          cr
     1co      pdgpsi)
  53  format(//67h  akemax   werg       serg       qwcycle   qtcycle    qw
     1lpm     qtlpm)
```

```
 54  format(//67h     t1         t2         t3          t4           t5          t
    16        beats)
      stop
      end
c -----------------------------------------------------------------------------
c
c ssss  Subroutine for computing deflection of rubber valve flap  sssssssss
c
      subroutine ydist(p,y)
c
      common/flap/a,b,tv,er,poisr,cdamp,freq
c
      opp=1.+poisr
      omp=1.-poisr
      tpp=3.+poisr
      fpp=5.+poisr
      s=b/a
      s2=s*s
      s4=s2*s2
      a4=a*a*a*a
      alns=alog(1./s)
      t1=4.*(1.-s2)*tpp/opp
      t2=16.*s2*opp*alns*alns/(omp*(1.-s2))
      t3=4.*s2*tpp*alns/omp
      t4=(1.-s4)*fpp/opp
      c1=p*a4*3.*opp*omp/(er*tv*tv*tv*16.)
      y=c1*(t1+t2-t3-t4)
      return
      end
c -----------------------------------------------------------------------------
c
c  sssssss Subroutine for computing oscillation of rubber valve flap sssssss
c
      subroutine oscil(zi,zim1,dt0,dt,zip1)
c
      common/osc/vmass,wn,cdampt
c
      rh=dt/dt0
      rhp1=rh+1.
      cdtv=cdampt*abs(zi-zim1)/vmass
      deno=2.+cdtv*rhp1+wn*wn*dt0*dt*rhp1
      avib=(2.+2.*rh+cdtv*rhp1)/deno
      bvib=2.*rh/deno
      zip1=avib*zi-bvib*zim1
      return
      end
c ---------------------------------------------------------------------------
c
c sssssss Subroutine for computing drive pipe velocity sssssssssssssss
c
      subroutine vpipe
c
      common/gen/ctp,cte,ctda,ctr,ap,arpo,arop,vpi,vpim1
     1      ,voi,vpmax,qwaste,pr,dt,pstat
      common/dimen/h,dp,tp,al,alo,do,dor,de,ddv
      common/prop/den,vis,ew,es,pois
      common/coeff/cp,cdv,cd,ca,cr1,cr2,co
c
c  vvvvvvvvvvvvvvvvvvvv   velocity computations  vvvvvvvvvvvvvvvvvvvvvv
      re=den*vpi*dp/vis
      if(re.gt.2100)go to 1010
      f=64./re
      go to 1020
1010  f=.316/(re**.25)
1020  continue
      reo=den*arpo*vpi*do/vis
```

```
      if(reo.gt.2100.)go to 1030
      fo=64./reo
      go to 1040
1030  fo=.316/(reo**.25)
1040  continue
c
      akt=1.+co+ctp+cte+ctda+ctr+arop*arop*f*al/dp
     1      +fo*alo/do
      bb=.5*voi*voi*akt/al
      vpi=(9.81*h/al-bb)*dt+vpim1
      voi=vpi*arpo
      pr=pstat-.5*den*vpi*vpi
      return
      end
c     -----------------------------------------------------------------
```